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MNOGOLETNIYE KOLEBANIYA GIDROLOGICHESKIKH KHARACTERISTIC BALTIYSKOGO, BARENTSEVA I KASPIYSKOGO MOREY I SOLNECHNAYA AKTIVNOST'

(Annual Fluctuations of Hydrological Characteristics of the Baltic, Barents and Caspian Seas and the Solar Activity)

by

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Abstract

The interrelation between the secular fluctuations of solar activity and the hydrological characteristics of the Baltic, Barents and Caspian Seas is investigated. It is found that the solar activity has not a direct effect on the seas but that it acts through the atmospheric circulation over the Atlantic-Eurasian sector of the Northern Hemisphere - namely, through the predominance of either the western (cyclonic) or eastern (anticyclonic) type of circulation in a given period of time. Observational data disclose that the hydrological characteristics affected most by the type of atmospheric circulation determined by solar activity are: changes of salinity for the Baltic Sea, of iciness for the Barents Sea and water level for the Caspian Sea. The interrelation among the phenomena is further defined by superimposed integral curves characterizing the variation of solar activity with time, the recurrence of atmospheric circulation types, and variations of salinity in the Baltic Sea, iciness in the Barents Sea and water level in the Caspian Sea.

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ANNUAL FLUCTUATIONS OF HYDROLOGICAL CHARACTERISTICS OF THE BALTIC, BARENTS AND CASPIAN SEAS AND THE SOLAR ACTIVITY

The twenties and the beginning of thirties of the present century mark changes in the annual march of atmospheric circulation over the Atlantic-Eurasian sector of the Northern Hemisphere [10, 16]. These changes have not a regional but a wider character. As has now been established, large-scale climatological changes began as long ago as the end of the nineteenth century and they embraced the entire globe. The changes of atmospheric circulation over Europe caused substantial changes of hydrological conditions in the Caspian, Barents and Baltic Seas.

The solar activity is the main cause of the occurring metamorphoses and intensity of atmospheric circulation [4, 9, 10, 19]. It is a complex cyclic phenomenon. In addition to the well-pronounced cyclic fluctuation within a period of 11 years, the solar activity is characterized by cyclic fluctuations having different periods - shorter (5 to 6 years, for instance) as well as longer, which are reciprocally superimposed over one another.

Among the cyclic fluctuations with long periods, a nearly secular cycle (80 to 90 years) of solar activity, which was detected by M. S. Eygenson [19], should be pointed out. He considered that the profound changes of climate occurring in the twentieth century, the warming of the Arctic for instance, are the consequences of the current secular cycle of solar activity.

I. V. Maksimov [12] explains the secular fluctuations of iciness in the North Atlantic Ocean, the continental character of climate in Europe, the mean Caspian Sea level and other hydrometeorological phenomena by superimposure of two cyclic fluctuations having a large period: 80 years, caused by secular changes of solar activity, and 250 years, associated with the period of changes in the speed of earth's rotation.

Of great interest are the investigations conducted by A. A. Girs [10] relative to the connection between solar activity and atmospheric circulation. These investigations introduce a substantial refinement into the law of the "accentuation of baric field" which was formulated by E. E. Fedorov and V. Yu. Vize. The essence of the law is that an increase of solar activity leads to a sharpening of baric relief, in connection with which the baric gradients increase and atmospheric circulation is intensified. According to the authors, the solar activity does not influence the type of circulation.

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Subsequent investigations conducted by L. A. Vitel's [9] and N. A. Belinskiy [4], who deal with the same problem of reciprocity between solar activity and atmospheric circulation on the basis of cyclo-anticyclonic activity, contain very important results confirming once again the effect of solar activity on the intensity of atmospheric circulation.

According to the investigations by A. A. Girs [10] and later by N. I. Tyabin [16], the solar activity determines not only the intensity but also the type of atmospheric circulation, which depends on the secular march of solar activity. Thus, for instance, it follows from the mentioned study by A. A. Girs, which

deals with G. Ya. Vangengeim's [6] indexes of atmospheric circulation, that during the periods that are marked by attenuation of solar activity the processes of western type of atmospheric circulation become anomaly developed in the atmosphere, whereas during the periods that are marked by intensification of solar activity the processes of eastern and meridional circulation become anomaly developed. The mentioned relationship is of great prognostic significance not only for the extended long-term forecasting of atmospheric circulation but also for hydrological forecasts because the anomaly sign in the fluctuations of hydrological elements (water temperature, iciness, etc.) depends on the type of circulation.

The secular fluctuations of solar activity, which are of great geophysical significance, are presented in figure 1.

In plotting the graph characterizing the solar activity, the annual deviations from the standard Wolf numbers, W, were utilized. At our disposal are sufficiently dependable data on the indexes which have been averaged on the basis of the sliding 11-year periods since 1749. This means that after the annual deviations from the standard had been determined, the sliding averages by 11-year periods were computed, but then, on the basis of the data the integral sums were found and the integral curve was plotted.

The average values based on sliding 11-year periods were calculated with a view to eliminating the effect of the 11-year cycle of solar activity and to obtaining the secular march of Wolf numbers in a more or less pure form. The

presentation by means of integral curve is convenient for the reason that it expresses the general trend in the development of the process for a lengthy /5 time period. The trend is expressed by the direction of the curve. The downward and upward directions indicate the anomalous development of the process

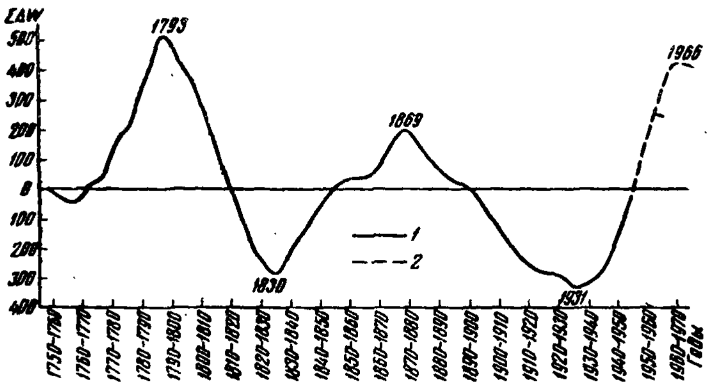

Fig. 1. Integral curve of annual deviations from the standard (averaged on the basis of sliding 11-year periods) Wolf numbers, W.

1 — observed; 2 — forecast.

in the respective time periods. In the first instance, the anomaly indicates attenuation, but in the second instance, intensification of the process in relation to the standard value; the horizontal direction of the curve reflects its normal intensity. The integral curve, W, has been plotted for a period from 1749 to 1956 and continued (dashed line) to 1975; for the plotting we used the data of long term forecasts of solar activity which had been prepared

by the Physics Division of the Pulkovo Astronomical Observatory.

The secular cycle of solar activity is expressed very clearly. Two complete secular cycles with a period of 77 years have been determined during the mentioned period. The numbers at the maximums of the curve correspond to the respective mean year (see fig. 1).

Hydrological Conditions in the Baltic Sea

The annual temperature and salinity fluctuations in the Baltic Sea water, as well as the water exchange through Danish Straits [14, 15], are considerable and have a cyclic character. The period embracing for instance the recent quarter of the century is typical, first of all, by a general rise of the sea water, salinity and temperature (of the bottom layers), as well as by considerable variations in the water exchange through Danish Straits, which create substantial changes in the biology of the sea; this, incidentally, has furthered a considerable increase in catches of certain species of fish. In connection with long range planning of the development of fisheries in the Baltic Sea it is important to know whether the indicated trend is lasting or the current cycle of conditions that had began in the thirties will be terminated in the immediate future.

In the twenties of this century the water salinity in the central part of the sea and in the Gulf of Finland decreased, but at the beginning of the thirties a lengthy cycle of general increase in the salinity of the sea began. Certain quantitative characterization of the process is presented by the following table:

VARIATION OF SALINITY IN THE BALTIC SEA

Area	Years	Salinity S, $^{o}/_{oo}$
North Coast of the Gulf of Finland (from Söderskär to Bengtskär)	1930	5.38
	1953	6.72
Gottland Depression (layer from 150 to 225 M)	1933	11.37
	1953	13.32
Bornholm Depression (horizon - 90 M)	1930	14.90
	1953	19.09

In order to determine the main causes for the general increase in the salinity of the Baltic Sea, which began at the beginning of the thirties, it is necessary to examine annual fluctuations in the water exchange through Danish Straits [15]. Since the end of twenties, the water outflow from the Baltic steadily decreased. In the thirties, also a decrease of another component of water exchange -- /6 namely, the water influx into the Baltic Sea -- occurred; this decrease was, however, less intense in comparison with the attenuation of water outflow from the sea. Such trend of the two components was caused by a decrease in the resultant water exchange through the straits.

The immediate cause for the decrease of water outflow from the Baltic Sea in the thirties is the diminishing of river influx, which has led to a lowering of sea level and a diminishing difference between the sea levels of the Baltic and North Seas. The decrease of river influx in the Baltic Sea Basin in the thirties was, in turn, caused by considerable changes in the character of atmospheric

circulation - namely, by the weakening of cyclonic activity and intensification of anticyclonic regime over the territory of Europe.

An illustrative characterization of the occurring changes in the forms of atmospheric circulation in Europe during the mentioned time period is presented in figure 2. In it one can see the integral curve of deviations from the standards of the circulation index, according to Vangengeim, which expresses the recurrence of the number of days characterized by the forms of western transport. Since the thirties, the curve slopes abruptly and steadily, which indicates a general weakening of cyclonic activity in Europe. Thus, the water

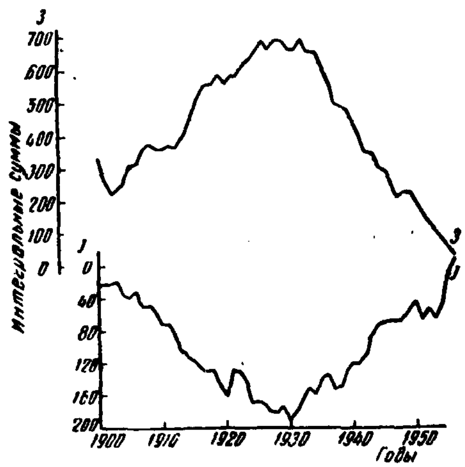

Fig. 2. Integral curves of annual deviations from the standard number of days with western circulation, 3, and the number of deep cyclones, J, over Europe (4-th area of the synoptic catalogue).

Key. Abscissa: years
Ordinate: integral sums

and salinity exchange through the straits is associated with the intensity and character of atmospheric circulation in Europe.

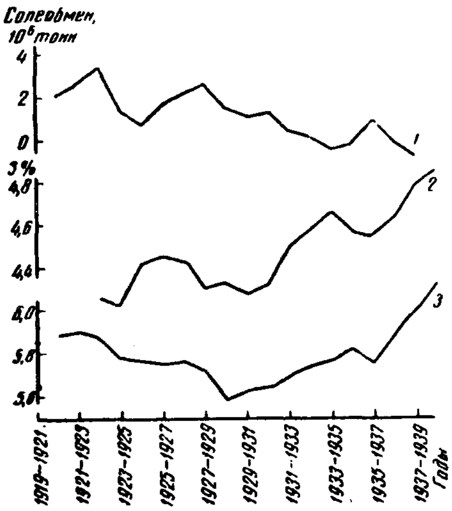

Fig. 3. Annual fluctuations of salinity exchange through Danish Straits and of salinity in the Gulf of Finland.

1 - quantity of salt exchange in millions of tons; 2 - water salinity at Tammio (layer from 0 to 20 M); 3 - water salinity of the Gulf of Finland (layer from 0 to 30 M).

Key. Abscissa: years
Ordinate: salinity exchange, 10^6 tons

The indicated trend in the water and salinity exchange through the Danish Straits could not be without effect on the salinity regime of the Baltic Sea during the mentioned period, which is pointed out also by K. Wyrtki [21]. In order to have an idea of the connection, the superimposed graphs depicting the

sliding mean annual magnitudes based on three-year periods of salinity exchange through the straits and the water salinity in the Gulf of Finland are presented in Figure 3. The graphs show that the decrease of salinity exchange through the Danish Straits in the thirties corresponds to a general increase of water salinity in the Gulf of Finland and, consequently, in the Baltic Sea.

Because the water and salinity exchange occurring through the Danish Straits is associated with atmospheric circulation, the increase of salinity in the Baltic Sea was ultimately determined by the intensification of anticyclonic activity over Europe; this led to a decrease of continental runoff and of differences in sea levels between the Baltic and North Seas, which, in turn, caused a decrease of water and salinity exchange through the Danish Straits. A diminished salinity exchange means a decreasing intensity of the outflow of salts from the sea, their accumulation in it and, as a result of the whole process, salinification of the sea.

The general level of salinity in the Baltic Sea is also determined by the immediate and direct effect of continental runoff which is expressed by a greater or smaller degree of dilution of sea water in connection with the rather great annual fluctuations of river discharge. After 1930, as a result of great diminishing of river discharges, a substantial attenuation of its dilutive action took place, which also contributed to the increase of salinity in the sea [14, 21].

Further, as a result of the development of anticyclonic activity during the thirties and the subsequent years, the intensity of the deep compensatory current

in Kattegat and the Danish Straits, which feeds the Baltic Sea with a water of high salinity, increased. The general link between the deep current and the type of atmospheric circulation was clearly demonstrated by R. Kändler [20]. It is during the anticyclonic regime, which is usually marked by weak activity of winds, that the development of the deep compensatory current in the straits between the Baltic and North Seas is most pronounced.

The general rise of salinity in the bottom layer over the Darser Ridge [14, 20] from 1927 to 1929 is an indirect indicator of increase in the intensity of the deep compensatory current. When examining the annual fluctuations of salinity in the layer, one can see that the period from 1927 to 1929 characterizes a break in the general trend. Since then, a general increase of salinity in the bottom layer over the Darser Ridge began, which is indicated by increase of intensity of the deep compensatory current.

Thus, also the deep current contributed to the increase of salinity in the sea after 1930, but this factor is of smaller significance than the salinity exchange and the continental runoff. Such a conclusion can be substantiated by the fact that the area crossed by the deep current passing across the Darser Ridge occupies not more than 0.09 km^2 and it is insignificant.

Summing up the discussion, it can be concluded that the general salinification of the sea, which has occurred since 1930, is due to the following factors: weakening of water and salinity exchange through the Danish Straits, decrease of continental runoff in the Baltic Sea Basin and intensification of the deep current in Kattegat and Danish Straits. It is of essential significance that

the three factors are interrelated, have a similar effect on the salinity regime of the sea and are the consequences of a durable development of anticyclonic activity over Europe, which was beginning at the end of the twenties and the start of the thirties.

During the years, one more factor acted in this direction: against the background of general attenuation of water exchange, the cases of a very intense influx of the saline Kattegat waters into the Baltic Sea recurred comparatively more frequently, which were caused by the impact of westerly storm winds. On the basis of investigations concerning the annual fluctuations of salinity in the main depressions of the Baltic Sea [14] it was established that a voluminous influx of Kattegat waters had occurred in 1934, 1938, 1948 and 1952. The relative uniformity and a not too infrequent recurrence of voluminous inflow of saline waters are, evidently, associated with increasing recurrence of deep cyclones over Europe and, consequently, with the storm winds affecting the water exchange through the straits [15] — all of which takes place against the background of general attenuation of cyclonic activity. /8

The increasing occurrence of deep cyclones paralleled with the attenuation of cyclonic activity after the thirties is illustrated by a graph, B, in figure 4. The graph has been plotted on the basis of data presented by L. A. Vitel's and it represents an integral curve of annual deviations from the standard number of deep cyclones (pressure in the center 990 mb and less) over Europe to the north of lat. 55° (4th area of the synoptic catalogue prepared by Vitel's). The curve shows the period from 1900 to 1956.

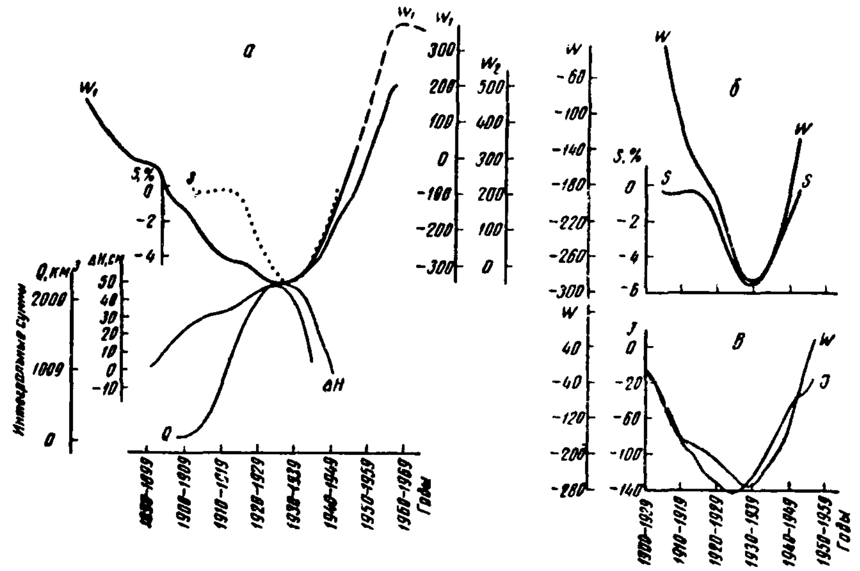

Fig. 4. Integral curves of annual deviations from the standard Wolf number, W (averaged on the basis of sliding decades), of salinity, S °/oo, at Helsinki, of differences, ΔH, between the Baltic Sea level (Hanko; Swedish name Hangö) and Kattegat sea level (Warburg), of water exchange through Danish Straits, Q, and the number of deep cyclones over Europe, J.

<u>Key</u>. Vertical line, left: integral sums.

Simultaneously with the variation of salinity and water exchange, substantial fluctuations of water temperature in the Baltic Sea have taken place. In the surface layer, a general rise of water temperature has been observed from the end of the twenties almost to the end of the thirties, which was in complete agreement with the general rise of water temperature. In the deep layers of the sea, the trend of temperature rise required a longer time period and it was still observed in the early fifties, i.e. when the salinity of water increased in the layers.

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The warming of bottom layers is also explained by a more frequent recurrence of voluminous influx of Kattegat waters into the Baltic Sea against the background of general weakening of water exchange through the straits.

It can be seen from the discussion that the annual fluctuations of water salinity and temperature (in bottom layers) of the Baltic Sea and, in particular, the observed trend of their growth during the recent quarter of the century, are closely linked with annual fluctuations of water exchange through Danish Straits and the continental runoff but, if we widen our outlook, the association can be extended to the lengthy and large scale processes of atmospheric circulation over Europe.

According to the latest research conducted by A. A. Girs, the durable anomalies of various types of atmospheric circulation formulated by Vangengeim are a result of the secular variation of solar activity; this means that there is a relationship between the annual fluctuations of hydrological regime in the Baltic Sea and the secular variation of solar activity. This assumption was

verified by comparing the integral curves characterizing the deviation from the standard Wolf numbers with analogous curves characterizing some of the hydrological aspects of the Baltic Sea. In figure 4, a, one can see the integral curves of the following elements: Wolf numbers, W; salinity, S, based on water surface observations at Helsinki; water exchange, Q, through Danish Straits and differences between water levels, ΔH, of the Baltic Sea (Hanko; Swedish name Hangö) and Kattegat (Warburg).

The integral curves, W_1 and W_2, pertain to the current secular cycle (1870 to 1956) and to the first secular cycle (1749 to 1883), respectively; they have been obtained from the general integral curve plotted for the entire period of observations on sunspots (1749 to 1956). Although both of the curves pertain to various secular cycles, they are united by having the same type of anabatic branches as well as by corresponding to very high secular maximums of solar activity. The mentioned curves are superposed in figure 4, a, so that their maximums coincide.

The integral salinity curve, S, has been plotted for a nearly 50 year period (from 1905 to 1952). For the integral curve of water exchange, Q, the series from 1898 to 1944 have been used, but for the ΔH curve, the series from 1891 to 1949.

In figure 4, δ, are superposed the integral curves, W and S, for a similar time period. Naturally, in this case the overall pattern of connections between the elements will be truer because the conditions of comparison have been more accurately accounted for.

The comparison of the four integral curves of various hydrological aspects, which are presented in figure 4, has led to very interesting results. During the period marked by a secular attenuation of solar activity (downward slope of integral curve), the difference between the water levels of the Baltic Sea and Kattegat (fall of sea level) is above the usual. The same trend is observed in water exchange. As for the salinity of the sea, it, in contrast to the first two hydrological aspects, shows a well pronounced trend of a general attenuation during this part of the secular cycle, i.e. the dilution of the sea. During the period marked by intensification of solar activity, the pattern of anomalous state of sea level, water exchange and salinity assumes a character that is in direct contrast to the former. This indicates a trend toward increase in salinity, i.e. toward the salinification of the sea.

Thus, the integral curves illustrate the reciprocal connection and tie of annual fluctuations in water level differences, ΔH, between the Baltic Sea and Kattegat, of water exchange, Q, through Danish Straits and of salinity, S, in the Baltic Sea. It should, however, be noted that the connection is materialized by means of atmospheric circulation which appears to be an intermediate link in the process. In the light of the discussion, the scheme of interaction among various factors can be presented as follows. The secular variation of solar activity determines directly the lengthy anomalies in the development of atmospheric circulation forms over Europe, which in turn exercise influence on hydrological conditions in the Baltic Sea.

The disclosed general correlation in the secular march of integral curves characterizing the solar activity and in a number of interrelated hydrological aspects of the Baltic Sea enables us to formulate a sufficiently substantiated assumption on the probable trend in the development of hydrological conditions in the Baltic Sea for many years ahead.

The current secular cycle of solar activity is characterized, as can be seen from figure 4, a, by the anabatic branch of integral curve, W. In other words, the present period of the secular cycle is characterized by intensified solar activity in comparison with its standard value. According to a long term forecast, the analogous trend of solar activity will continue to the beginning of the sixties.

On the basis of this, and of the identity in the secular march of integral curves characterizing the solar activity and surface water salinity in the Baltic Sea, it should be assumed that the cycle of a general rise in the water salinity of the Baltic Sea, which had began a quarter of a century ago, will probably cease at the beginning of the sixties. By this time, the value of water salinity should be about its standard magnitude.

It is necessary to note that the forecast of the probable annual development of salinity in the surface layer of the Baltic Sea accounts for the effects of such factors as the resultant water exchange through Danish Straits, the continental runoff and intensity of the deep compensatory current. However, besides this, very substantial annual changes in the salinity of the sea and the temperature of the bottom waters occur, as was pointed out above, during the

intervals marked by the influx of the more salty Kattegat water.

In order to form an idea on the future trend in the development of the factor, it is necessary to examine the problem on the relationship between the solar activity, W, and the recurrence of deep cyclones, J, over Europe, insofar as they determine the probability of a voluminous water influx through Danish Straits and, consequently, the contribution of the factor to changes occurring in the hydrological conditions in the Baltic Sea.

The relationship between the two mentioned factors is characterized in figure 4, б, where the graphs of integral curves presenting the annual deviations from the standard values of deep cyclones over Europe (to the north of parallel 55°) and of Wolf numbers are superposed. Their plotting does not differ from the analogous curves presented in figure 4, a. As to the time, the curves pertain to a period from 1900 to 1956. A rather great similarity between the integral curves, W and J, is indicated by the fact that during the period marked by a secular attenuation of solar activity one must expect a decrease in the recurrence of (with regard to the standard value) deep cyclones in the given area, whereas during the period marked by a secular intensification of solar activity one must expect an increase in the recurrence.

This conclusion corresponds to the results obtained earlier by L. A. Vitel's [9] who made a detailed investigation of the relationship between solar activity and the intensity of atmospheric circulation in individual areas and in the entire natural synoptic region of Europe.

Thus, a simple relationship exists between W and J; in addition, an extended long term forecast of W is known, which is presented in figure 4, a, by a dashed line that is a continuation of the integral curve of solar activity and /11 its anabatic branch of the current secular cycle.

It is evident that the integral curve, J, must continue to go up to the beginning of sixties, i.e. the frequency of deep cycles over Europe will probably be above the standard value up to the mentioned time. Such an assumption is linked with the probable trend in the recurrence of voluminous influxes of Kattegat waters and, therefore, the possible effect of the latter factor on hydrological conditions of the Baltic Sea, i.e. on its water salinity and temperature of bottom layers, must be expressed in the presentation of the existing anomaly in its magnitude during the years immediately ahead. Thus, further on, the action of the given factor coincides with the action of the factors determined by the resultant water exchange, continental runoff and intensity of the deep current; therefore there is a reason for leaving unchanged the long term forecast for salinity of the Baltic Sea, which was discussed above.

Iciness of the Barents Sea

V. Yu. Vize was one of those who had investigated the relationship between the iciness of the Barents Sea and the solar activity [8]. Demonstrating such a relationship, he found that its sign was not constant. Thus, from 1896 to 1912 the relationship was inversed, from 1913 to 1935 it was direct, then again the reversal of the sign had taken place. According to V. Yu. Vize, "the constancy of the sign of relationship between the number of sunspots and hydrological

elements in temperate and high latitudes can be explained by the fact that the fluctuations of solar activity affect the intensity of atmospheric circulation but not its type", in other words, by the accentuation law of baric field. At the present time, however, a substantial correction relative to the nature of the relationship between solar activity and the types of atmospheric circulation need be introduced into the concept of the law.

Further, the following basic assumptions were introduced when the problem was being discussed: 1) there exists an obvious relationship between the secular variation of solar activity and the type of atmospheric circulation and 2) the iciness of the Barents Sea and its long term variations depend on the baric regime [7] or, more specifically, on the type of atmospheric circulation. Both of the assumptions combined lead to the logical conclusion that, ultimately, the cause of secular fluctuations of iciness in the Barents Sea are the secular fluctuations of solar activity.

In order to verify the mentioned assumption, the secular march of solar activity must be compared with the iciness of the Barents Sea. Such a comparison has been made with the aid of integral curves which, owing to the method of their plotting that is based on the sliding mean 11 year magnitudes, show the secular characteristics of the elements compared. The integral curves of the mean iciness in the May-June period, $S'_{ice(V-VI)}$ and the mean value of solar activity in the November-March period, W_{XI-III}[1] are presented in figure 5 (unbroken curves).

[1] The period chosen for W is based on the fact that in spring the iciness is determined by meteorological conditions in the preceding cold time period.

The Wolf numbers for November and December pertain to the preceding year. The characterization of iciness, S'_{ice}, was based on the area occupied by ice and expressed in percentages with respect to the entire sea area. The integral curves for S'_{ice} and W were based on data obtained in the period of 1900-1954. /12

For the sake of comparison, there is another pair of curves (dotted lines) in the figure. The calculation of the latter was based on the mean W values for the year but the calculation of S'_{ice} on the values for the April-August period. As can be seen, both variations of the corresponding curves are of the same type, which indicates that the secular march of solar activity and iciness in the Barents Sea is uniform and well pronounced.

It appeared that during the periods that were marked by attenuating secular activity of the sun the iciness of the Barents Sea was above the standard value (increased) but during the periods marked by intensified activity of the sun it was below the standard value (decreased).

In order to obtain a calculative relationship between the same elements, special graphs were plotted; on their horizontal axis the Wolf numbers, W_{XI-III}, averaged on the basis of sliding 11 year periods, were laid off but on vertical axis the analogous magnitudes of iciness, $S'_{ice(V-VI)}$. Special graphs were plotted for synchronous relationships and for relationships characterized by a displacement of iciness relative to the solar activity by 1, 2, 3 and 4 years. The relationships were expressed by curves; the closest of them pertains to a displacement by 2 years (fig. 6). This relationship is expressed approximately by the /13

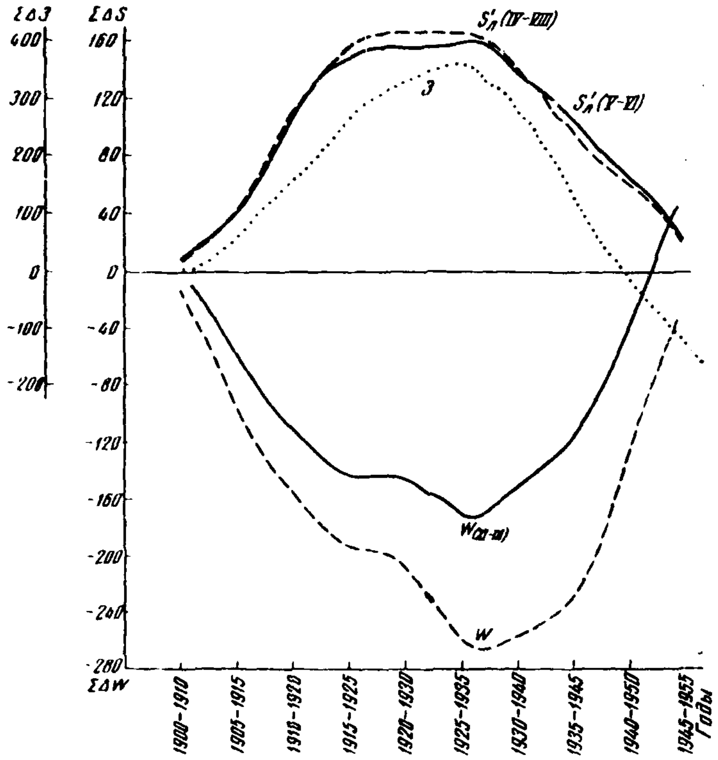

Fig. 5. The integral curves of annual deviations from the standard values (averaged) based on the sliding 11 year periods of Wolf numbers, W, of iciness in the Barents Sea, S_{ice}, and recurrence of the number of days characterized by the western circulation, 3.

following equation:

$$S'_{ice}\ (V\text{-}VI) = \frac{1935}{W_{XI\text{-}III}} + 0.18\ W + 2.5, \tag{1}$$

where $S'_{ice(V-VI)}$ and W_{XI-III} have the same meanings as before.

Two curves are presented in figure 6. When drawing one of them (the heavy one), the writer kept in mind the gravitational centers of the 6 groups into which the entire field of the points marking the relationship was divided. The other curve (the thin one) corresponds to the equation shown above. By using the relationship (the heavy line in fig. 6), we calculated the secular march of iciness during the whole period of observations and further to the 11 year period from 1965 to 1975; the calculation was based on the extended long term forecasting of solar activity. The calculated data have been compared with analogous magnitudes based on observations. A completely satisfactory agreement between the results was obtained. This indicates that the existing trend of a decreased secular iciness of the Barents Sea will be preserved to the middle of the sixties after which a general rise of the secular iciness in the sea must begin.

In order to characterize the extreme values of iciness in various periods of its secular mar[illegible] annual fluctuations was superposed over the graph of secula[illegible] iciness. It was established that the secular march is clearly ma[illegible]ly in the averaged data but also in the extreme magnitudes of iciness. Thus, in the period characterized by a diminished secular iciness, its greatest values for individual very severe years (1942 for

instance) were considerably (to 20 °/o) smaller than the values of iciness in analogous years occurring in a period characterized by an increased iciness of the sea (1917 for instance). The same can be said about the exceptional years characterized by a small degree of iciness. In connection with the discussion, the general intensification of secular iciness, which has been forecast for the sixties, will also mark an increase of its extreme values in very severe and very mild winters.

In addition to the integral curves of iciness and solar activity, an integral curve characterizing the frequency of the number of days marked by the western form of circulation (dotted line) is presented in figure 5. The curve has been plotted in exactly the same way as the other curves shown in figure 5 and therefore it characterizes the secular variations of the frequency of western form of circulation. The overall connection between the integral curves, 3 and S'_{ice}, is obvious: the secular iciness of the Barents Sea is intensified during the period marked by an anomalous secular development of the western form of circulation and attenuated during the period marked by an /14

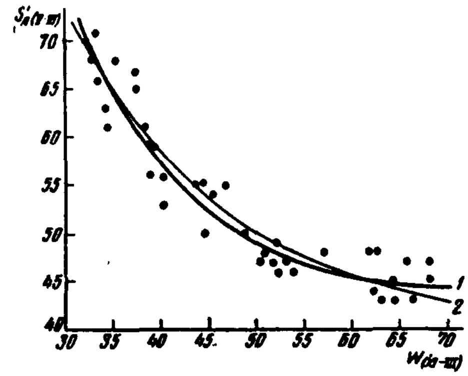

Fig. 6. Graph showing the relationship between the mean sliding (by 11 year periods) values of Wolf numbers, W, and the iciness of the Barents Sea, S_{ice} (S'_{ice} is displaced relative to W by 2 years).

1-on the basis of gravitational centers of the 6 groups of points marking the relationship; 2-on the basis of equation (1).

anomalous weakening of the latter.

The substance of the given relationship is determined by the following. The interlatitudinal air exchange abates during the western circulation in connection with zonal displacement of Icelandic cyclones over northern Europe [10]. Owing to this, the negative radiational balance in northern latitudes is not compensated by heat advection. As a result, a negative air temperature anomaly is observed in circumpolar areas, which leads to a higher degree of iciness. During the period marked by a secular abatement of the western type of circulation, the recurrence of the eastern type becomes more frequent because the two forms of circulation are interlinked, having a mirror-like march [10]. But at the eastern type of circulation, the cyclones, moving from the Icelandic low and circumventing the European anticyclone, are displaced into the northern latitudes of the Barents Sea, thus causing attenuation of iciness in the area. Consequently, in the development of the eastern type of circulation or, correspondingly, in the abatement of recurrence of the western type of circulation, the iciness of the Barents Sea must be diminished as to the secular relationship.

Our aim in this case is not to obtain quantitative relationships between atmospheric circulation and iciness. The qualitative characteristics mentioned above are sufficient for explaining the overall character of relationship between secular fluctuations of solar activity and iciness of the Barents Sea because the predominance of one or the other type of circulation in the given era is determined by the secular march of solar activity.

Heretofore we have discussed the secular fluctuations of solar activity and iciness of the Barents Sea and the interrelation between them. Of interest is also the problem on small scale cyclic fluctuations of the mentioned aspects. As is known, the eleven-year cycles are the main fluctuations characterizing the solar activity and being very well pronounced. They can be separated from secular fluctuations and the same can be done with respect to iciness. The singling out of the eleven-year cyclic fluctuations from the summary data was realized as follows: the sliding mean values of the eleven-year periods were deducted from the annual data of W or S'_{ice}; the results were then smoothed in the form of sliding means by five-year periods. The processing results of the Wolf numbers and iciness of the Barents Sea were expressed by two graphs. For solar activity, one can expect well pronounced cyclic fluctuations of W numbers by eleven-year periods; but the iciness of the Barents Sea is also characterized by completely accountable analogous fluctuations. However, the phase of reciprocal march of these aspects is not stable.

It is interesting to note that exactly the same comparison for the surface water temperature in the North Atlantic (Iceland area and to the south of Greenland) is presented in a study by N. A. Belinskiy [4]. The graphs of changes in water temperature and solar activity plotted by him are identical to the graphs of iciness of the Barents Sea and solar activity; even the years marked by shifts in the sign of relationship almost coincide. All this shows that the type of relationship between the eleven-year periods of cyclic fluctuations in solar activity and iciness of the Barents Sea is evidently not accidental but having a rather widespread character.

What has been said above serves as a basis for the following assumption relative to the regularity in the alternation of the sign of relationship between the mentioned aspects. The sign, evidently, changes after two cyclic fluctuations with eleven-year periods. Thus from 1910-1914 to 1930-1934 the /15 relationship between the Wolf numbers and the iciness of the Barents Sea was direct, but from 1931-1935 it was inverse; prior to 1910-1914 it was also inverse. Let us compare the periods marked by direct and inverse relationship between W and S'_{ice} derived by the writer and V. Yu. Vize. The comparison shows that the periods had coincided rather closely between themselves. But after analysing them it becomes clear that the instability of the sign of relationship pertains only to the cyclic fluctuations of iciness in the Barents Sea and solar activity which are marked by eleven-year periods; as to the secular fluctuations of the aspects, the sign of relationship is stable but inverse, as was pointed out above.

It follows from what has been said that the secular as well as eleven-year fluctuations of iciness in the Barents Sea are determined by solar activity. It is interesting to note that even such abrupt variations of iciness as were observed after 1917 or after 1931 are also caused by variations of solar activity.

Thus, if the assumption on regularity in the alternation of the sign of relationship between the cyclic fluctuations of solar activity with a period of eleven years and the iciness of the Barents Sea should be confirmed in the future, the extended long term forecasts of secular variations in iciness could be essentially refined.

The Caspian Sea Level

The problem of the Caspian Sea is characterized by the existing low water level. The general process of the fall of the Caspian Sea level is continuing for about 75 years, but in acute form it appeared, as is known, since 1930. During the last quarter of the century the Caspian Sea level has dropped by 2.5 meters. Many authors [2, 3, 11] have studied this phenomenon and their conclusions are in essence nearly similar. The fall of the Caspian Sea level is associated with the setting in of a period marked by a sharp development of anticyclonic regime over Europe, which has led to attenuation of precipitation, including the hibernal precipitation, in the Volga Basin — the main water source feeding the Caspian Sea. The decrease in the quantity of precipitation caused a substantial and lasting abatement of water influx into the Caspian Sea, which resulted in the fall of its water level because the water discharge from the Volga equals approximately 80 % of the discharge from the rivers flowing into the Caspian Sea and a little more than 60 % of the entire water mass received by the basin. During the last years the fall of the Caspian Sea level occurs also as a consequence of economic activity of man, which is associated with the use of river discharge for the purposes of hydro-energetics, irrigation, etc.

The abrupt fall of the Caspian Sea level has caused considerable difficulties, bringing great losses to many branches of national economy. The continued fall of the sea level will, naturally, increase the losses. The solution to the situation lies in artificial regulation of the Caspian Sea level.

In connection with the problem of regulating the Caspian Sea level, of very great significance is a dependable extended long term forecasting of it with a higher degree of probability than in the case of using the methods developed by N. A. Belinskiy and G. M. Kalinin [3]. A number of such forecasts have been prepared during the recent years. Some of them (forecasts by B. A. Appolov) have been advanced to numerical formulations, others (forecasts by M. S. Eygenson, I. V. Maksimov) have a rather qualitative character. /16

The forecast by B. A. Appolov [2] is based on relationship between the mean air temperature of Moscow area and the Caspian Sea level for a long time period (25 to 50 years). According to this forecast, the Caspian Sea level during the immediate 10 to 15 years must recess by 30 to 50 cm as a result of warming up of climate; taking into consideration also the economic activity of man, the recession may reach 1.5 to 2 meters.

The extended long term forecast by M. S. Eygenson [18, 19] is based on the relationship between secular fluctuations of the Caspian Sea level and solar activity which was calculated by him. This comparison enabled M. S. Eygenson to draw the following conclusion [19]: "...The low water level of the Caspian Sea corresponds as a rule to the periods of secular maximums of solar activity; and, vice versa, the high water level of the sea corresponds usually to the periods of secular minimums of solar activity". Having based his forecast on the given relationship between the Caspian Sea level and solar activity as well as on the assumption that the present eleven year cycle of solar activity is the upper cycle in the current secular march of solar activity, the investigator concludes "that the period from 1970 to 2000 will be marked by a more or less higher secular level of the Caspian Sea".

I. V. Maksimov considers that in the immediate future[1] "one can expect cessation in the recession of the Caspian Sea level and a new relative rise of it". Having established that the secular fluctuations of great hydrometeorological phenomena are cyclic fluctuations marked by two periods - 80 years and 250 years - I. V. Makarov demonstrated by this that the first half of the current century would be characterized by simple (having one sign) fluctuation phases; this fact has caused a series of substantial changes in climate, including the fall of the Caspian a level after 1930. Determining the mean magnitudes of periods and amplitudes in the cyclic fluctuations of the most important hydrometeorological phenomena, the investigator arrived at a number of prognostic conclusions as a result of analysis. Such a conclusion dealing with the Caspian Sea is discussed below. 7

Thus, there are two opinions on the possible fluctuations of the Caspian Sea level under the impact of climatic conditions during the immediate 15 years. These opinions are contrary and they point out a necessity for further investigation of the important problem.

The extended long term forecast of sea level, which is proposed by this study, is based, as in a study by M. S. Eygenson c18, 19ɔ, on relationship between the fluctuations of mean Caspian Sea level and solar activity. However, the investigational methods used in these two studies differ substantially from each other.

In order to determine the general relationship between the fluctuations of solar activity, W, and the Caspian Sea level, H, their integral curves were

[1]The study was published in 1954.

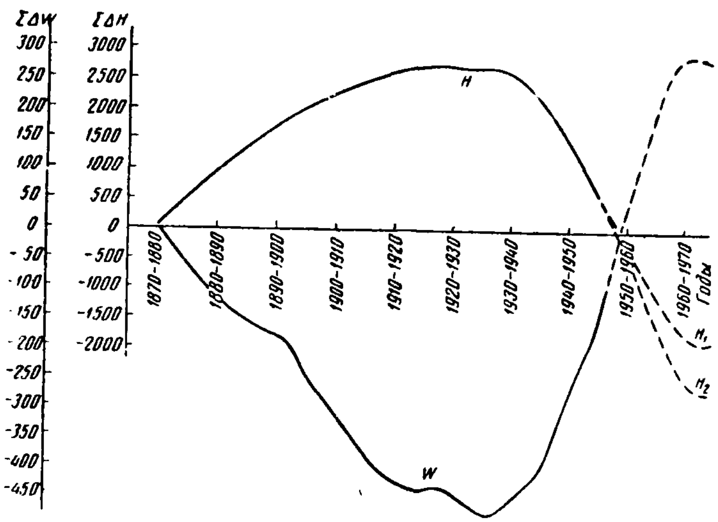

Fig. 7. Integral curves of annual deviations from standard values (averaged on the basis of the mean eleven year period) of the Wolf numbers, W, and the Caspian Sea level, H.

been plotted for one period, owing to which the conditions of comparability have been observed. They characterize the secular cycle of solar activity and the sea level because the cyclic fluctuations of the latter marked by a period of eleven years were eliminated. Comparison demonstrates that the integral curves of Wolf numbers and the mean water level of the Caspian Sea have a mirror-like march. This means that, with respect to secular fluctuations, the mean water level of the Caspian Sea in periods marked by attenuation of solar activity is above its standard level and, vice versa, in periods marked by intensification of solar activity the Caspian Sea level is below its mean annual level. The mentioned result agrees entirely with conclusions drawn by M. S. Eygenson [18, 19] concerning the relationship between fluctuations of the

compared, which permitted a more distinctive determination of linkages in the development of the main trend in the variation of the mentioned aspects. A series of the mean monthly and yearly data on the Caspian Sea level reduced to the readings of the Baku gauging rod of 1928 and corrected by taking into consideration the submergence of the instrument is presented in a study written by B. A. Appolov and E. I. Fedorov c13. The series beginning from 1830 and being continuous from 1837 was utilized in this study.

Not all of the period of observations on sea surface has been used for a comparison with solar activity but only the part covering the last secular cycle of solar activity, which was determined on the basis of integral curve (see fig. 1), i. e. from 1870. The limitation of the series was done by taking into consideration the ideas based on conclusions by I. V. Makšimov concerning the agreement among the phases of cyclic fluctuations of long periods (85 years and 250 years) during the first half of the twentieth century, which were disclosed in a number of large scale hydrometeorological phenomena in the northern hemisphere (including fluctuations of the Caspian Sea level) and which have various causes - namely, solar activity and varying speed of earth's rotation, respectively. By virtue of the conclusion, the mentioned period characterized by a combination of phases of two cyclic fluctuations is most agreeable to the analysis discussed here - namely, to clarify, first of all, the secular relations between solar activity and the Caspian Sea level. /17

Figure 7 superposes the integral curves of the Wolf numbers, W, and the Caspian Sea level, H, for the present secular cycle of solar activity. The curves have

Caspian Sea level and solar activity.

Thus, the general link between secular fluctuations of solar activity and the mean water level of the Caspian Sea, which was discussed relative to the current secular cycle, is obvious. Further, we attempted to give it a computational /18 character, for which a graph of relationship between the Wolf numbers and the Caspian Sea was constructed. The relationship between integral sums of Wolf numbers and mean values of the Caspian Sea level was sufficiently close. This relationship is characterized in figure 8, б. Here the secular march of Caspian Sea level from 1870 to 1955 is presented (on the basis of data showing deviations from standard values) which has been smoothed by taking into consideration the sliding eleven year periods.

The dotted lines demarcate the same sea level computed on the basis of Wolf numbers. As can be seen, the curve coincides rather closely with the unbroken line, repeating it well, In figure 8, a, the graphs of smoothed secular variation of sea level are superposed over the actual annual fluctuations. Comparison between the two graphs shows that the secular fluctuations of the Caspian Sea level form the basic background over which the fluctuations with a considerably smaller amplitude and period are superposed.

Dots on the lower curve (fig. 8, б), beginning from 1951 (the period of eleven years from 1946 to 1956), need be considered as prognostic and determined by climatic processes only. In correspondence with the mirror-type character of variations in the integral curves, W and H, the downward moving branch of the latter, beginning from the eleven year period of 1945-1955, was extrapolated

into the eleven year period from 1965 to 1975. The extrapolation was carried out in two variables, H_1 and H_2; the extrapolated segments of the integral curve characterizing the sea level are presented in figure 7 by dots.

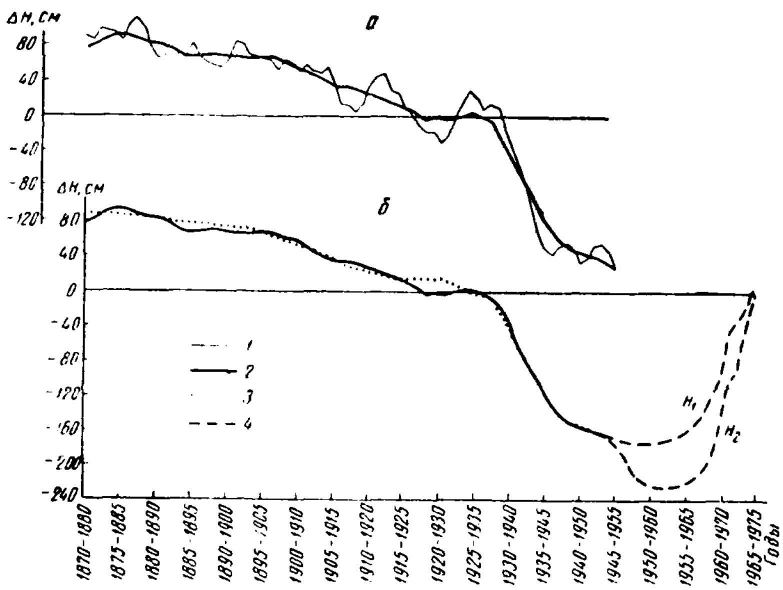

Fig. 8. Graph of annual fluctuations of the Caspian Sea level (relative to the standard level).

1 - the actual yearly sea level; 2 - smoothed by taking into consideration the sliding eleven year periods; 3 - computed; 4 - forecast.

Having found the variation of integral curves, W and H, for 1965-1975, it was not difficult to present relationship between the elements in figure 8, б, where the probable secular variation of the Caspian Sea level was extended to the /19 eleven year period from 1965 to 1975. Here the assumed secular changes in sea

level are shown in two variables: H_1 and H_2. According to the variable H_1, insignificant recession of the Caspian Sea level under the impact of climatic factors is to be expected at the beginning. Later, from the eleven year period lasting from 1957 to 1967, a completely stable trend toward the rise of the sea level is assumed to be setting in. According to the other variable, H_2, initial recession of sea level will be more noticeable and it will reach 40 to 50 cm, but, as in the first case, since the eleven year period from 1957 to 1967, a stable and rapid rise of the Caspian Sea level is in the offing. Thus, both of the variables discussed indicate that the sixties of this century will mark the turning point for the secular march of the Caspian Sea level and that in this decade its general rise will begin.

The difference between the two variables of the assumed secular variations in sea level (fig. 8, б) gives an idea on the limits within which the true sea level must lie.

This discussion has dealt with the secular fluctuations of the Caspian Sea level that depend upon the secular march of solar activity. Inasmuch as the eleven year cycle of solar activity is defined very explicitly, an attempt to determine its effect on flucutations of the Caspian Sea level has been made. For the purpose, the cyclic fluctuations of the Wolf numbers and the Caspian Sea level with a period of eleven years were singled out of the observed annual data. They were then compared in order to elucidate the relationship between them. If the eleven year cycle of solar activity is very explicitly and correctly expressed, the Caspian Sea level is characterized by cyclic fluctuations having

a short period whose duration varies from 7 to 16 years. Therefore the most diverse phase combination of H and W curves occurs.

In addition to the Wolf numbers, another indicator of solar activity - namely, the index of recurrence, a, by M. S. Eygenson [17], which expresses the stability and intensity of sunspot formation, was utilized for the purpose.. Taking into consideration the index, L. A. Vitel's [9] disclosed that the number of deep cyclones over the North Atlantic Ocean and the Polar Basin has a considerably closer relationship with the index a than with the Wolf numbers.

We made a similar attempt. It was disclosed that the link between sea level and index a is rather closer than that between the former and index W; however, it cannot be considered as sufficiently close. The average amplitude of cyclic sea level fluctuations with a period of eleven years does not exceed 18 cm, being more frequently less than 10 cm.

Thus, in comparison with secular fluctuations of the Caspian Sea level, the cyclic eleven year fluctuations are of a considerably smaller significance. Consequently, when they are superposed over the future variation of sea level, presented in figure 8, б, the latter must vary little. The main result obtained before remains in force: in the sixties, the recession of the Caspian Sea level should end and its general rise must begin.

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In connection with the investigation of relationship between the secular fluctuations of solar activity and the corresponding hydrological characteristics of the Baltic Sea (salinity, water exchange), Barents Sea (iciness) and

the Caspian Sea (water level) it was stated that the solar impact on hydrosphere is not exerted directly but through the atmospheric circulation. The seas are subjected to the action by the system of atmospheric processes /20
occurring in the Atlantic-Eurasian sector of the Northern Hemisphere. Therefore the secular changes in the most important hydrological aspects of the mentioned seas are reciprocally interlinked and tied with atmospheric circulation as well as with solar activity.

This is illustrated in figure 9. All the mentioned integral curves characterizing the processes of secular march of solar activity W, the recurrence of atmospheric processes of the western type (according to G. Ya. Vangengeim) 3, the Caspian Sea level H, iciness of the Barents Sea S'_{ice}, and salinity of the Baltic Sea S, are superposed in the figure.

As can be seen from figure 9, the integral curves H, S'_{ice} and 3 have a simple phase but it is opposite to the phase of W and S. The simple phase of the integral curves, H and 3, underscores once more the known assumption of L. S. Berg [5] - namely, that during the periods that are characterized by average water level in the Caspian Sea the Arctic seas have a high degree of iciness; and vice versa, during the periods that are characterized by low water level in the Caspian Sea, the Arctic seas have a decreased iciness. This conclusion could be expanded to mean that during the periods of increased /21
secular iciness in the Barents Sea and a high Caspian Sea level, the Baltic Sea is subjected to the process of dilution; vice versa, during the periods of decreased iciness and low water level in the mentioned seas, the salinity of the Baltic Sea increase.

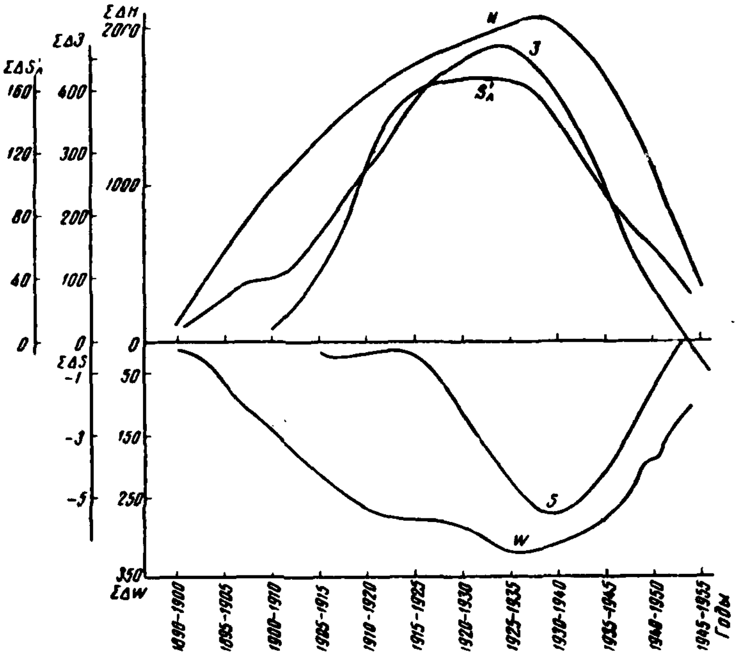

Fig. 9. Integral curves of annual deviations from standard (averaged on the basis of sliding eleven year periods) Wolf numbers, W, of the number of days with western form of circulation, according to Vangengeim З, of the iciness of the Barents Sea, S'_{ice}, of the Caspian Sea level, H, and the salinity of the Baltic Sea, S.

Thus, we can now add the Baltic Sea to the interlinked system of the two seas - the Caspian and Barents Seas. The secular changes of hydrological characteristics in the mentioned seas are caused by the atmospheric circulation in the Atlantic-Eurasian sector. This is indicated by the form of the integral frequency curve presenting the western type of atmospheric circulation, 3.

The iciness of the Barents Sea is determined by a greater or smaller heat advection which depends on the fact whether the zonal or meridional transfer of water masses prevails during the given period in the Northern Hemisphere, notably, in the Atlantic-Eurasian sector.

As to the Caspian Sea level and the Baltic Sea regime, the secular metamorphoses of atmospheric circulation forms are expressed primarily by secular fluctuations in the quantity of precipitation over Europe, which depend on the type of atmospheric circulation. The periods during which the zonal transport prevails are marked by a greater quantity of precipitation, whereas the periods during which the eastern type of atmospheric circulation prevails are marked by a smaller quantity of precipitation.

Thus, despite differences in the mechanics of impact, the secular variations of iciness in the Barents Sea, of water level in the Caspian Sea and of salinity regime in the Baltic Sea have one common immediate cause: the secular metamorphoses of atmospheric circulation forms in the Atlantic-Eurasian sector of the earth. However, as has now been established, the secular variation of one or the other type of atmospheric circulation in the Northern Hemisphere depends definitely on solar activity (the W and 3 curves in fig. 9). Therefore, in

final analysis, changes in solar activity can be considered as the cause of secular fluctuations of hydrological conditions in seas, notably, the Baltic, Barents and Caspian Seas.

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